NATIONAL BUREAU OF STANDARDS REPORT

8997

THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY
OF TWO SPECIMENS OF BERYLLIUM COPPER STRIP

by

T. W. Watson and D. R. Flynn
Environmental Engineering Section
Building Research Division
Institute for Applied Technology

Report to

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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1. INTRODUCTION

This report presents results of thermal conductivity and electrical resistivity measurements in the temperature range -140 to 200 °C for two samples of beryllium copper strip submitted by the National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland.

2. SAMPLES

The two samples were furnished to NBS in the form of rolled strip material, 0.002 inch thick by 2 inches wide. Sample 1, Be-Cu alloy 25 strip, was purchased by the National Bureau of Standards from the Brush Beryllium Company on their work order No. RE7171 and was identified on the packing list as "12351-389 4 100 Brush Be Cu alloy 25 strip copper alloy No. 172 condition XHMS; tensile 194,000 psi." The tag attached to the material identified it as "Brush mill heat-treated beryllium copper 190 alloy." This material was in the form of a continuous length of flat strip. Sample 2, alloy 125 strip, was furnished to NBS by Goddard Space Flight Center in the form of two lengths of strip that had been formed into "tubing" of about 1.2 cm diameter, with one side of the strip over-lapping (but not connected to) the other side by about 90 degrees. This "tubing" had been opened up to be flat and then rolled onto spools of about 3-cm diameter. When unrolled, the strip would spring back into tubular form. Two spools were given NBS. The spool containing the larger amount of material was wrapped with olive-brown tape and labeled "Alloy 125 bare deployed partially." The other spool was wrapped with black tape and labeled "125-190 HT bare."

The test specimens were fabricated from the strip material, as follows:

2.1. Be-Cu 25 Strip, Sample 1

A composite bar specimen, 1.78 cm wide by 1.75 cm thick by 25.4 cm long, was formed by stacking together 350 pieces (cut from the flat strip material), each having a dimension of 0.0050 cm thick (table 1) by 1.78 cm wide by 25.4 cm long. The 350 strips were compressed and fastened together with seven 2-56 phosphor bronze screws through

tapped holes in the stack, beginning with one at the center and the remainder approximately 3.51 cm apart in both directions along the central length of the composite bar. A brass cylinder 2.54 cm in diameter by 5.8 cm long, with a 1.35-cm hole 5.5 cm deep, was soft-soldered to each end of the composite specimen, making a specimen of an overall length of approximately 37 cm, as required for the thermal conductivity apparatus shown in figure 1.

2.2. Be-Cu 125 Strip, Sample 2

As only 68 feet of alloy 125 strip were made available to us, this specimen was made with smaller width and thickness than specimen No. 1 of alloy 25. A composite bar, 1.58 cm wide by 1.08 cm thick by 25.4 cm long, was formed by stacking together 217 pieces (139 and 78 cut from the spools wrapped with olive-brown and black tape, respectively) of the Be-Cu 125 strip material, each piece being 0.0050 cm thick (table 1) by 1.58 cm wide by 25.4 cm long. The pieces were compressed and fastened together with phosphor bronze screws, in a manner similar to specimen No. 1 with the following exception: due to the curvature of the alloy 125 strip material, it was necessary to use eight additional 2-56 UNC screws and nuts, one midway between adjacent phosphor bronze screws and one at each end of the composite bar, in order to flatten the sheets and hold them together as a rigid composite specimen.

No chemical analysis of either of the beryllium copper strip materials was furnished or made at the National Bureau of Standards.

3. THERMAL CONDUCTIVITY TEST APPARATUS AND METHOD

The thermal conductivity of the samples was determined by means of a steady-state flow of heat longitudinally in the bar specimen, with measurements of the temperatures existing at the ends of six consecutive, approximately 3.51-cm, spans along the central length of the bar. Each determination required a pair of tests at moderately different temperature conditions, and yielded values of thermal conductivity at six different mean temperatures [1]*.

The test apparatus is shown schematically in figure 1.

The specimen, a bar approximately 37 cm long and of uniform external dimensions over the metering length, was supported at the top (coolant) end concentrically within a stainless steel guard tube of 0.8-cm wall thickness, which in turn was held concentrically within a cylindrical outer container. The specimen was drilled at each end with a 1.35-cm hole 5.5 cm deep. An electrical heater was inserted and secured in the hole at the bottom (hot) end by a completely enclosing metal cap (in lieu of the strap shown in figure 1), and the supporting fixture at the top end provided a liquid-tight connection for circulating a coolant through the top drill hole.

*Figures in brackets indicate the literature references at the end of this report.

Temperatures along the specimen were indicated by seven thermocouples located symmetrically about the longitudinal center of the specimen, spaced approximately 3.51 cm apart, with one additional thermocouple near the bottom end of the specimen. Thermocouples were similarly located in almost exactly corresponding longitudinal positions on the guard tube.

The guard tube was equipped near its lower end with an external circumferential electric heater, as shown. The guard tube was cooled at the top by means of a copper-tube coil soldered circumferentially at a position corresponding in effect to that of the specimen coolant well. Coolant (liquid nitrogen at -196 °C or water at 40 °C) was pumped through the guard coil and specimen well in series connection, as shown.

The electrical heater for the specimen consisted of 26-gage nichrome heater wire threaded back and forth through longitudinal holes in a porcelain cylinder, 1.25 cm in diameter and 5.2 cm long. Its resistance at 25 °C was approximately 21 ohms. Current was brought to the heater through relatively large heater leads, to which separate potential leads were connected at the point where they entered the porcelain core. The heater was energized by an adjustable constant-voltage d-c source. Heater current and voltage drop measurements were made, using standard resistors and the high-precision manual potentiometer used for thermocouple observations. The guard was heated with alternating current governed by a sensitive temperature controller actuated by the guard temperature at a selected position.

The thermocouples were made from calibrated chromel and alumel 26-gage wires pressed into 0.041-cm holes in each end of the phosphor bronze screws, the junction being formed by the screw. The bare thermocouple leads were individually insulated electrically with high-temperature flexible sleeving wrapped around the specimen and led out into the powder insulation in the same transverse plane as the junction (one wire in each direction around the bar). The wires were brought out through the powder insulation near the guard tube. The thermocouples in the guard tube were electrically welded to form a spherical junction about 0.10 cm in diameter. The junctions in the guard were inserted into radially drilled holes, 0.11 cm in diameter and 0.17 cm deep, and tightly secured by punch pricking the metal around the hole. The wires were similarly brought out through the powder insulation. The longitudinal positions of the thermocouple junctions were taken as those of the centers of the phosphor bronze screws, or of the drilled holes, measured to the nearest 0.01 cm with a laboratory cathetometer.

Current leads (0.1-cm Pt) were attached to the two ends of the bar specimen for passing a direct current of about 8 amperes along the bar for making electrical resistivity measurements. The lead at the hot end was led in a flat spiral in the powder insulation, in a plane transverse to the bar axis, to near the inner radius of the guard tube, from which point it was electrically insulated with broken ceramic tubing and brought upwards through the powder insulation near the guard tube.

After installation of the specimen, the space between it and the guard tube was filled with diatomaceous earth powder insulation, which also was used to insulate the space surrounding the guard tube. The tests were conducted with the insulation exposed to atmospheric air.

In principle, if there were no heat exchange between the specimen and its surroundings, the conductivity could be determined from the measured power input to the specimen and the average temperature gradient for each of the six spans along the specimen, all of uniform known cross-sectional area. In practice, a perfect balance of temperatures between the bar and guard all along their lengths is not possible, because of differences in their temperature coefficients of conductivity, and the effect of the outward heat losses of the guard. In addition to heat exchanges between the bar and guard from this cause, a relatively smaller longitudinal flow of heat occurs in the powder insulation surrounding the specimen, and the contribution of the specimen to this heat flow must depend somewhat on the bar-to-guard temperature unbalance.

In order to evaluate the heat flow in the bar at the center points of each of the six spans, a partly empirical procedure was used. Two steady-state test runs were made with slightly different bar and guard temperatures and power inputs. In the two tests, the heat flow and the observed temperature drop from end to end of a given span differed, as did also the approximate integral with respect to length of the observed temperature differences between bar and guard, summed from the hot end of the bar to the span center point. It is thus possible to write for each span two equations (one for each test run) of the form

$$\frac{Ak\Delta t}{\Delta x} + fS = Q$$

where A is the cross-sectional area of the specimen,

k is the specimen conductivity at the mean temperature of the span,

Δt is the temperature drop from end to end of the span,

Δx is the length of the span,

fS represents the total net heat loss from the bar from its bottom end at the heater to the midpoint, x, of the given span, expressed as the product of S, which is the integral

$$\int_0^x (t_{bar} - t_{guard})dx,$$

and an average heat transfer coefficient f for the thermal path from bar to guard,

Q is the measured power input to the specimen heater.

The two equations written for each of the six spans of the bar can be solved simultaneously to determine k and f. For this to be strictly valid, k and f must have equal values in the two equations. Since the mean temperatures of the span in the two tests will in general differ slightly, and the conductivity of the bar may vary with temperature, a slight adjustment is made to the observed values of Δt so that k corresponds to the mean of the span mean temperatures in the two tests. The equality of f in the two tests is not so readily assured, but because the magnitude of fS in these tests was generally on the order of one percent of Q, a moderate difference in the values of f in the two equations would affect the solved value of $Ak/\Delta x$ only slightly.

Electrical resistivity measurements for each span were made at the end of, but at the temperature conditions existing at, each pair of runs for determining the thermal conductivity, by passing a d-c current of about 7.7 amperes along the bar, and observing the potential differences between adjacent chromel leads of the span thermocouples, with the current direction forward and reversed. The average of the two potential drops between two adjacent chromel leads indicated the net potential drop due to the current flowing in the span, and thus enabled calculation of its resistivity. Due to a slight warming of the bar during the period of current flow, the resistivity was assigned to correspond to the time-average of the span mean temperature over this period.

The computation of results directly from the observed data was effected by an IBM 7094 digital computer suitably programmed to compute the thermal conductivity, the electrical resistivity, and the corresponding mean temperatures, for each of the six spans.

4. RESULTS

4.1. Results Obtained Using the Thermal Conductivity Apparatus

The results of the thermal conductivity and electrical resistivity determinations, using the thermal conductivity apparatus described above, are shown in figure 2. The 18 individual values of thermal conductivity plotted for each specimen represent three sets of tests each with values for the six spans. The 20 values of electrical resistivity plotted for each specimen represent 18 measurements made concurrently with the thermal conductivity determinations and, in addition, the averages of two sets of data taken with the specimen isothermal with the room temperature, one set taken before and one after the thermal conductivity measurements were made.

For both the alloy 25 and the alloy 125 specimens, the individual thermal conductivity values plotted in figure 2 exhibit a root-mean-square deviation from the curves drawn through these data of slightly more than one percent, excluding the values represented by the solid triangles.

The solid triangles correspond to the hot end of the alloy 125 specimen. The electrical resistivity values for this span, including the room temperature values, indicate that something had happened to this part of the specimen before test, possibly overheating while soldering the brass extension onto that end of the specimen. The values represented by the solid triangles were not considered in deriving the smooth curve representing the thermal conductivity of the alloy 125 specimen.

For the alloy 25 specimen, the individual electrical resistivity values plotted in figure 2 exhibit a root-mean-square deviation of less than one percent from the straight line drawn through these data. For the alloy 125 specimen, however, the root-mean-square deviation of the data, excluding the values represented by the solid triangles, exceeds five percent.

4.2. Auxiliary Electrical Resistivity Measurements

The electrical resistivities of several individual strips of both alloys were measured at the ice point. The specimens were placed in series with a calibrated 0.001 ohm resistor and a regulated d-c power supply. The resistance of each specimen was determined by comparing the voltage drop across a pair of knife edges spanning the central 10-cm length of the specimen with the voltage drop across the standard resistor. In order to minimize thermoelectric effects, voltage drops in the specimens were measured with the current flowing normally and reversed, and the resultant values averaged. All voltage measurements were made using a precision d-c potentiometer.

The specimens used for these resistivity measurements were individual strips selected to be representative of the material utilized in fabricating the thermal conductivity specimens. The electrical resistivity values (at the ice point) which were obtained on these strips are presented in table 2. The specimen designations are the same as those in table 1 for the thickness measurements (which were made on specimens cut from material adjacent to the corresponding resistivity specimens). Since the electrical resistance measurements can be made quite accurately, the variations in resistivity for the different specimens of the same alloy are believed to be due to errors in the thickness determinations and to actual variations in the material.

4.3. Analysis of Results

The scatter of the data for the thermal conductivity of both specimens is about the same as that which is normally obtained for a solid specimen in this apparatus. The electrical resistivity data obtained in the thermal conductivity apparatus appear reasonably satisfactory for the alloy 25 specimen, but are quite unsatisfactory for the alloy 125 specimen.

The alloy 125 strip appeared to have an oxide film on one surface. It is believed that this oxide tended to electrically insulate the laminations in the alloy 125 composite specimen from one another, and thus did not permit a uniform electrical current density to be established in this specimen. The thermal resistance of this thin oxide layer does not appear to have been large enough to significantly affect the thermal conductivity determinations.

It is rather difficult to analyze the effect of the holes and bolts holding the laminations together; we estimate any error from this source to be less than one percent and have not attempted to adjust the data to compensate specifically for such an error.

We feel that the resistivity measurements made on the individual strips yielded more reliable data than did the resistivity measurements made on the laminated specimens. Our best estimate of the electrical resistivity of these two alloys was obtained by using the average values of the resistivities for the individual strip determinations at the ice point (table 2), and the temperature dependence of the resistivity as determined on the laminated specimen of alloy 25. The electrical resistivity of the alloy 125 specimen was assumed to differ from that of the alloy 25 specimen by an additive constant (Matthiessen's Rule); in view of the large scatter in the data for the alloy 125 specimen, this was deemed preferable to taking the slope of the line through that data. The distinction between these two procedures of deriving the electrical resistivity values of the alloy 125 specimen is mainly academic, however, since values obtained by either procedure agree within about one percent at all temperatures.

The electrical resistivity values, derived as discussed above, and the thermal conductivity values, as plotted in figure 2, are given in table 3. These values represent our best estimate of the thermal conductivity, k, and electrical resistivity, ρ, of the two alloys in the longitudinal direction of the strip supplied. Values of the quotient, T/ρ, of the absolute temperature divided by electrical resistivity, and of the Lorenz function, $k\rho/T$, are also tabulated in table 2.

4.4. Discussion of Results

In figure 3, the thermal conductivity values obtained in this investigation are shown plotted against temperature along with literature values for the thermal conductivity of beryllium copper. The data of Smith and Palmer were for an alloy of reported composition (percent by weight) 97.49 Cu, 2.24 Be, 0.27 Ni, and 0.06 Fe. The different values at a given temperature correspond to different heat treatments. The data given by Cone [4] were obtained by an unreported but "reliable laboratory" on a cast bar, containing 2.45 wt. % beryllium, in the quenched and hardened condition. The alloy measured by Zlunitzin and Saveljev [5] was reported to contain 98.49 % Cu and 1.5 % Be. The specimen of Berman, Foster, and Rosenberg [6], containing 2 % beryllium, was held at 300 °C for two hours prior to testing. The data of

Mikryukov [2] which are shown in figure 3 correspond to an alloy, containing 2 % Be, which had been annealed in vacuum at 400 °C for 6 hours. Mikryukov also reported data for several beryllium copper alloys containing smaller amounts of beryllium.

In figure 4, the Lorenz function, $k\rho/T$, is shown versus temperature for both the alloy 25 and the alloy 125 material. The theoretical Sommerfeld value, $L_0 = 2.443 \times 10^{-8} V^2/deg^2$, is shown for comparison. If the thermal conductivity in a normal metal were entirely due to conduction of heat by the "free" electrons, the Lorenz function would be expected to be less than the Sommerfeld value at low, but not too low, temperatures and then to asymptotically approach the theoretical value at temperatures above the Debye characteristic temperature (~50 °C for Cu). This type of behavior is observed for pure copper, for which the electronic component of thermal conductivity completely overshadows the component of thermal conductivity due to conduction of heat by the crystalline lattice. In the case of an alloy, however, there can be a significant lattice thermal conductivity contribution, causing the Lorenz function to have a value in excess of the Sommerfeld value at lower temperatures; this is the observed behavior for these two beryllium copper alloys. The observed increase of the Lorenz function above the Sommerfeld value, especially for alloy 125, at the higher temperatures is less readily explained and may be due to experimental errors in the thermal conductivity or electrical resistivity values.

Smith and Palmer [3] reported measurements of thermal and electrical conductivity of a large number of copper alloys at 20 and 200 °C. Up to a thermal conductivity value of about 3 W/cm deg their data conformed well to the straight line

$$k = 0.0239\frac{T}{\rho} + 0.075$$

where k is thermal conductivity (W/cm deg), ρ is electrical resistivity ($\mu\Omega$ cm), and T is absolute temperature (°K). In a recent paper, Powell [7] reported a large number of measurements made at the National Physical Laboratory on copper alloys that also conformed closely to the Smith and Palmer equation.

In figure 5, values of thermal conductivity, k, from table 3 are plotted against values of absolute temperature divided by electrical resistivity, T/ρ, also from table 3, for both of the alloys studied in this investigation. The Smith and Palmer equation is shown in figure 5 for comparison. The data of Smith and Palmer [3] for a beryllium copper alloy at 20 and 200 °C for four different heat treatments are also plotted in figure 5, as are the data of Mikryukov [2] for an annealed 2 % beryllium copper alloy.

4.5 Estimated Accuracy of Results

The uncertainty in the smoothed thermal conductivity values given in table 3 is believed to be not more than 3 percent for the Be-Cu alloy 25 strip, and not more than 5 percent for the Be-Cu alloy 125 strip, over the entire temperature range.

4.6 Thermal Conductivity in the Transverse Direction

Sixteen small strips of the alloy 125 material, 0.510 cm wide by approximately 5 cm long, were cut in such a way as to ensure that the width of each strip was very closely the same. Half of these strips (longitudinal) were cut with the long axis parallel to the direction in which the original strip material had been rolled, and half (transverse) were cut with the long axis perpendicular to that direction. Two longitudinal strips and two transverse strips were cut from material adjacent to the thickness specimens (table 1) and resistivity specimens (table 2), and labeled correspondingly. The electrical resistivity of each of these 16 strips was measured at the ice point, using a pair of needle points of 2.57-cm separation as potential taps.

All of the material tested exhibited a higher resistivity in the transverse direction than in the longitudinal direction, the average value of the ratio of the transverse to longitudinal resistivity being 1.021. Using the usual statistical procedures to calculate confidence intervals at the 95 percent level, the electrical resistivity of the alloy 125 material was 2.1 ±0.9 percent higher in the transverse direction than in the longitudinal direction. On the basis of this, we estimate that the thermal conductivity of the alloy 125 strips at 0 °C was about 2 percent less in the transverse direction than in the longitudinal direction. A few measurements also were made on the alloy 25 strip; these indicated no significant difference between the electrical resistivities in the transverse and longitudinal directions.

5. REFERENCES

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TABLE 1

Thickness of Two Beryllium Copper Samples
(Measured by the NBS Engineering Metrology Section)

Sample 1, Beryllium Copper 25 Strip

Specimen	Average thickness inch	Average variation in thickness microinches	Average Surface texture microinches AA
1	0.001959	7	5
2	.001993	5	4
3	.001957	8	4
4	.001952	6	4

The thickness of the specimens was measured between a flat and a 3/16-inch spherical contact under a force of 2½ ounces. The reported thickness is the average thickness of 25 positions on the specimen. The thickness has been corrected to zero load by means of the Hertzian deformation equations.

The surface texture is the arithmetic average deviation of the surface as measured with a 0.01-inch cutoff. The reported texture is the average texture of 12 positions on each specimen.

It is estimated that the thickness is accurate to ±10 microinches, and the surface texture is accurate to ±2 microinches.

Sample 2, Beryllium Copper 125 Strip

Specimen	Average thickness inch	Average variation in inches microinches
A	0.001993	6
B	.001980	9
C	.001932	8
D	.001995	12

The thickness of each of the specimens was measured between a flat anvil and a 3/16-inch spherical contact under a force of 2½ ounces. The reported thickness is the average for 12 positions measured on each specimen. The thickness values reported have been corrected for deformation due to the measuring force by means of the Hertzian equations.

It is estimated that the thickness is accurate to ±30 microinches at 68 °F.

TABLE 2

Electrical Resistivity at the Ice Point for Individual Strips of Two Beryllium Copper Samples

Sample	Specimen		ρ, $\mu\Omega$ cm
Alloy 25	1		8.07_8
	2		8.15_7
	3		8.06_8
	4		7.99_7
		Average	8.07_5
		Range	±1.0%
Alloy 125	A		6.80_3
	B		6.79_9
	C		6.54_9
	D		6.75_2
		Average	6.72_6
		Range	+1.1/-2.6%

TABLE 3

Best Estimates of the Thermal Conductivity and Electrical Resistivity of Two Samples of Beryllium Copper Strip

Temp., t °C	Electrical resistivity, ρ μΩ cm	Thermal conductivity, k W/cm deg	T/ρ °K/μΩ cm	Lorenz function (kρ/T) V^2/deg^2
		Beryllium Copper 25 Strip		
-140	6.79_8	0.512	19.5_9	2.61_4
-100	7.16_3	.616	24.1_7	2.54_9
-50	7.62_0	.733	29.2_8	2.50_3
0	8.07_5	.836	33.8_3	2.47_1
50	8.53_1	.929	37.8_8	2.45_2
100	8.98_6	1.016	41.5_3	2.44_6
150	9.44_2	1.098	44.8_2	2.45_0
200	9.89_7	1.180	47.8_1	2.46_8
		Beryllium Copper 125 Strip		
-140	5.44_9	0.618	24.4_4	2.52_9
-100	5.81_4	.742	29.7_8	2.49_2
-50	6.27_1	.875	35.5_8	2.45_9
0	6.72_6	.989	40.6_1	2.43_5
50	7.18_2	1.090	44.9_9	2.42_3
100	7.63_7	1.186	48.8_6	2.42_7
150	8.09_3	1.282	52.2_9	2.45_2
200	8.54_8	1.386	55.3_5	2.50_4

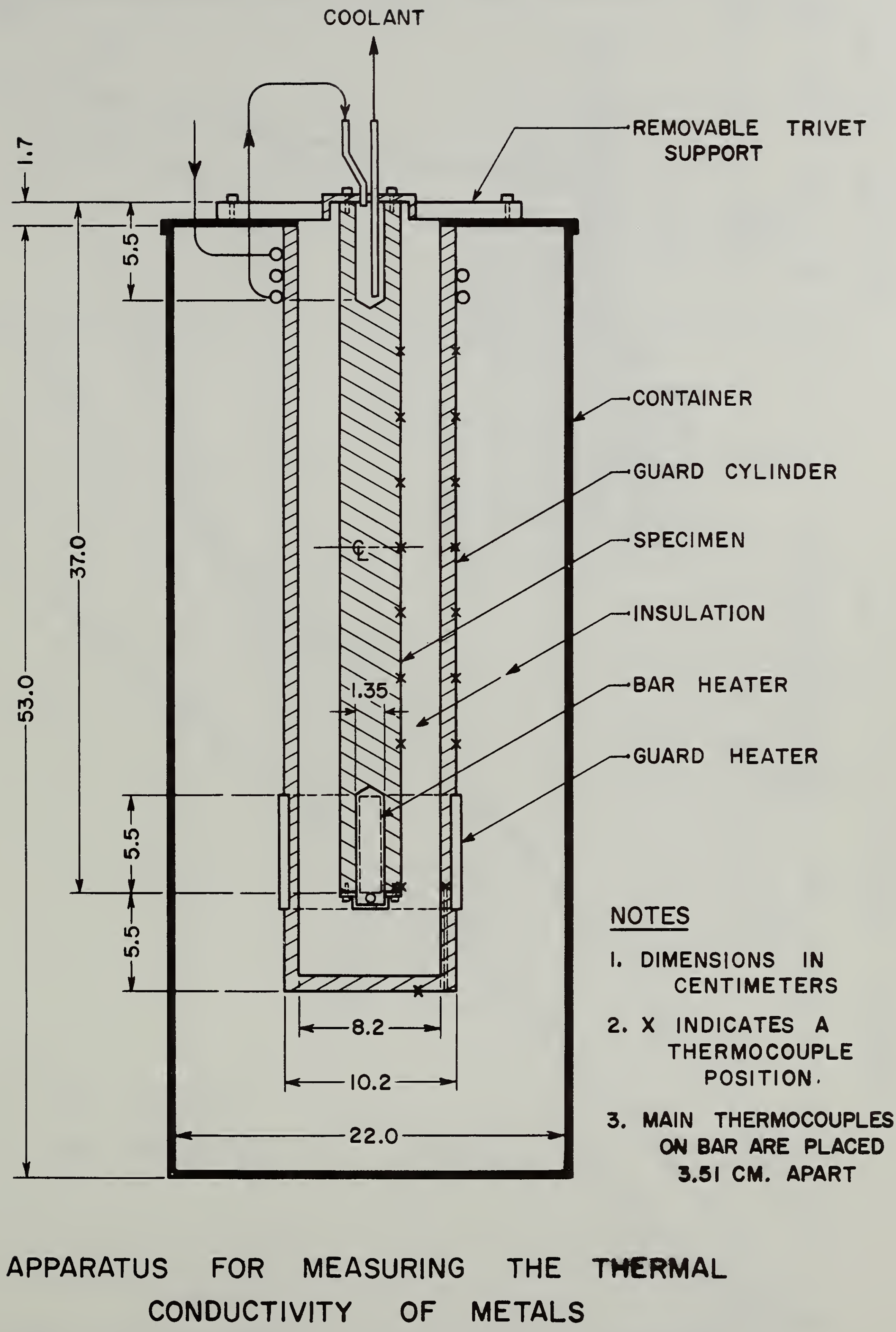

Figure 1. Apparatus for measuring thermal conductivity of metals.

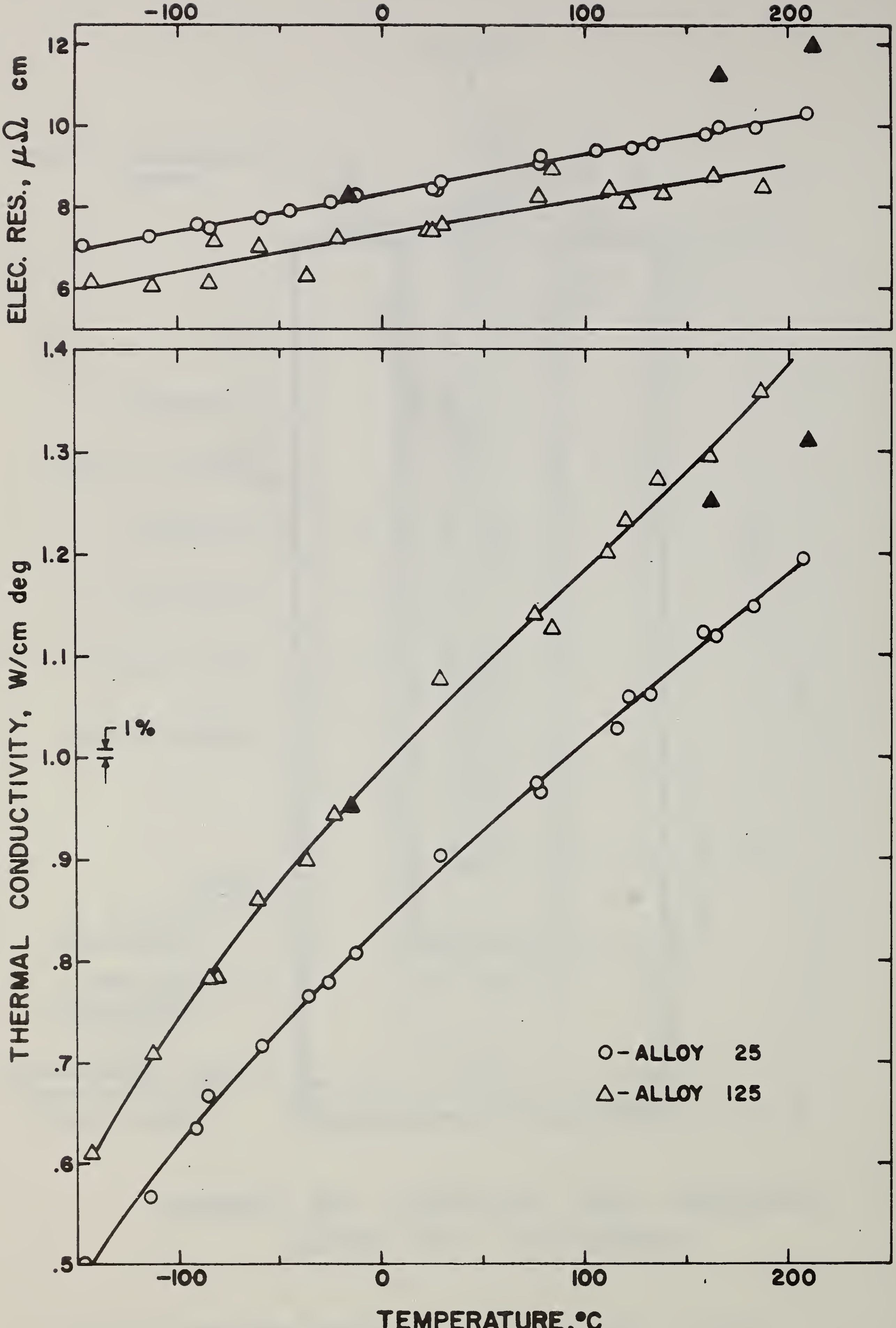

Figure 2. Thermal conductivity and electrical resistivity of two beryllium copper (2 wt. % Be) strip materials as measured in the thermal conductivity apparatus.

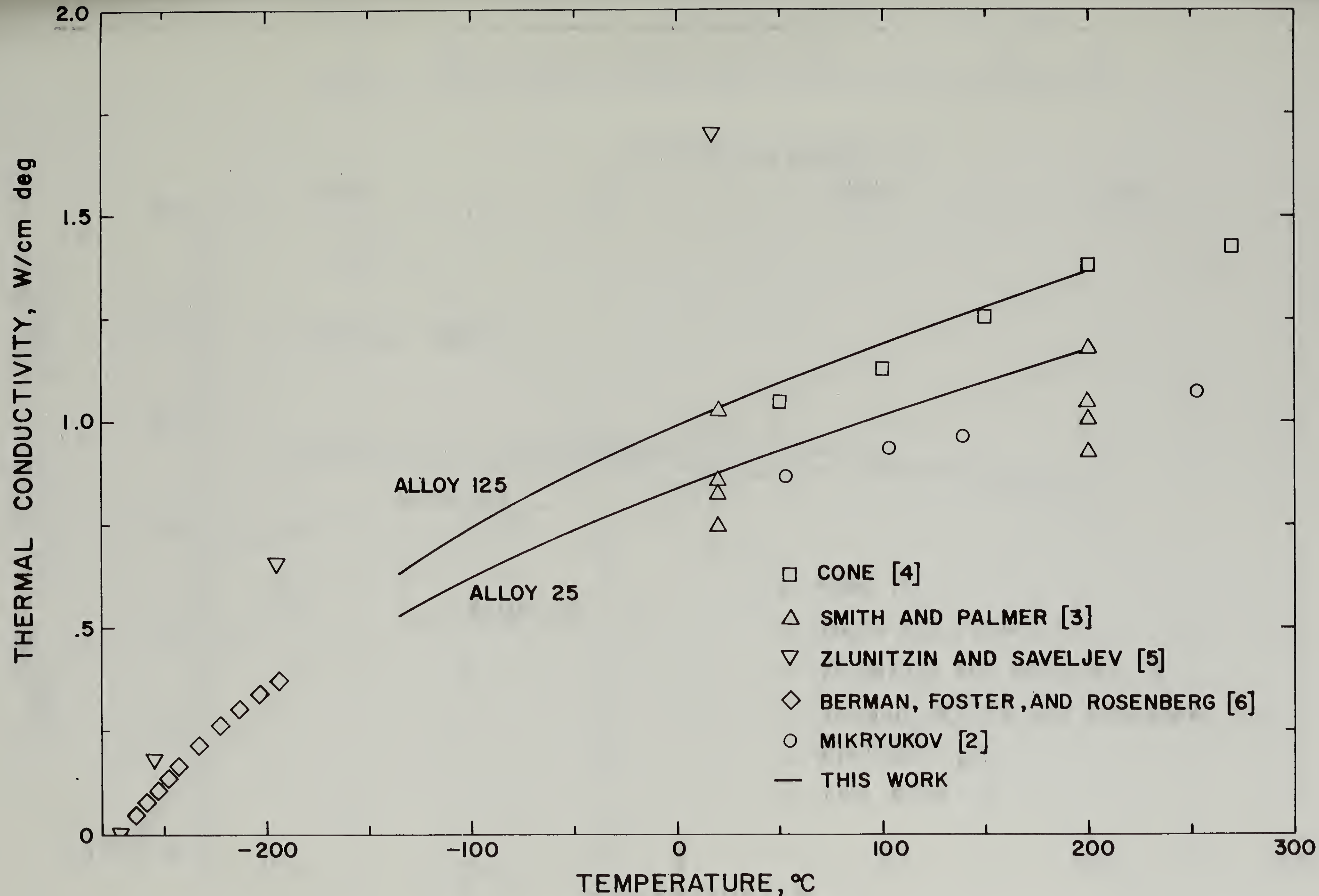

Figure 3. Thermal conductivity of beryllium copper alloys as determined in this investigation and as reported in the literature.

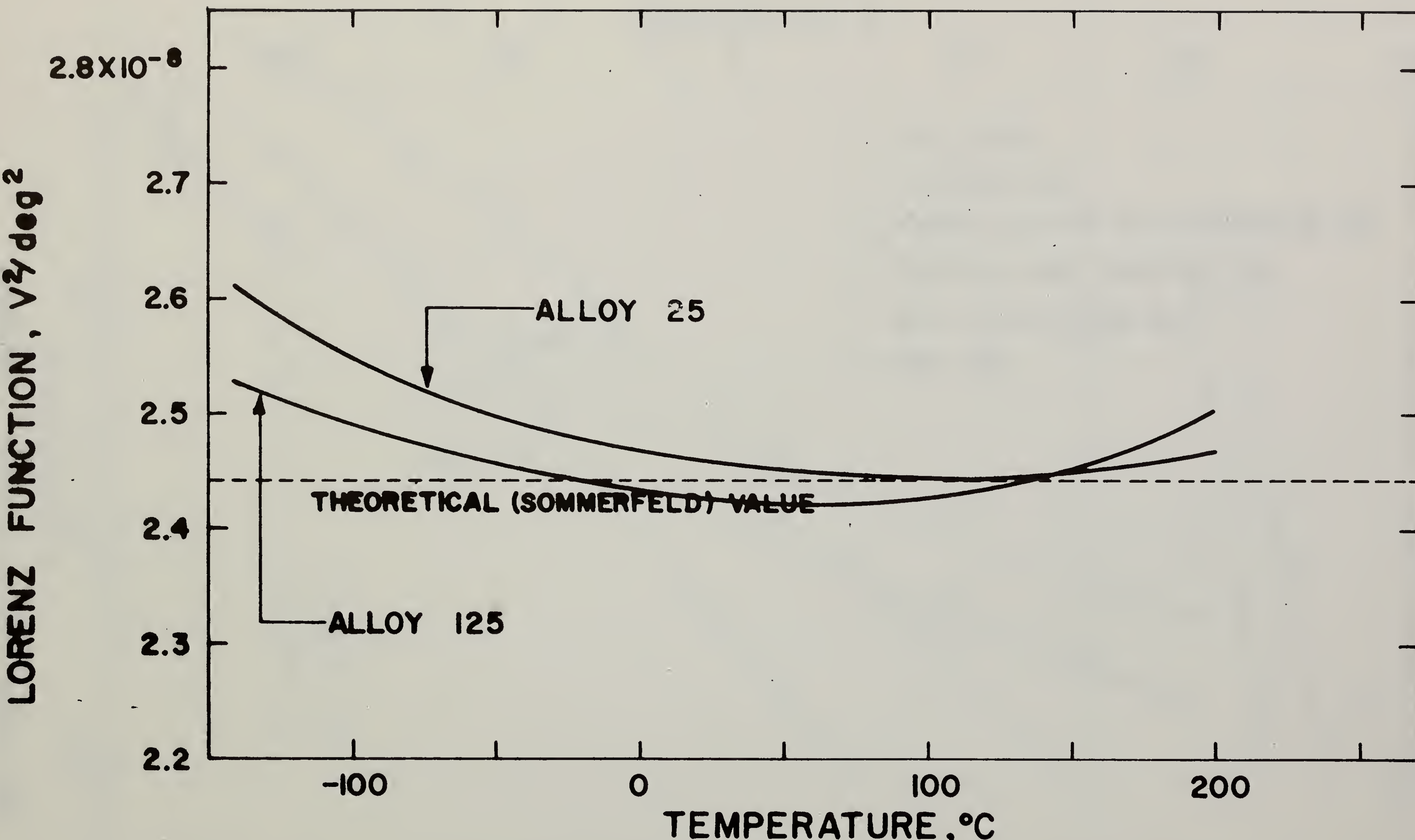

Figure 4. Lorenz function, $k\rho/T$, versus temperature for two samples of beryllium copper strip.

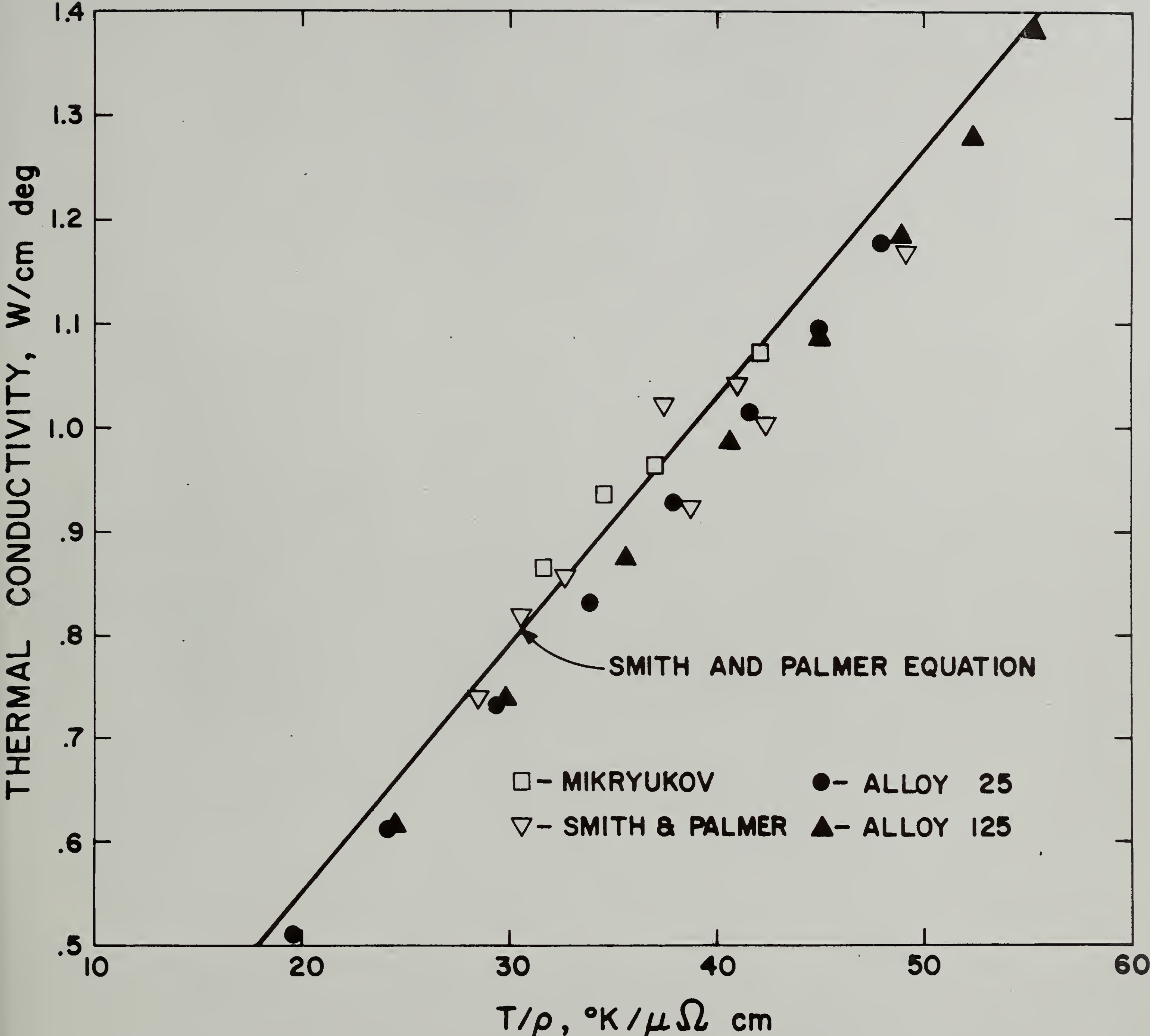

Figure 5. Thermal conductivity of beryllium copper plotted against absolute temperature divided by electrical resistivity.

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